Retrievals of Column Water Vapor Using Millimeter-Wave Radiometric Measurements

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***Abstract*—The airborne millimeter-wave imaging radiometer (MIR) measurements conducted over the midwest region of the continental United States during January/February 1997 and over the Alaska–Arctic region during May 1998 are used to estimate column water vapor $W < 0.8$ g/cm^2 under a clear sky. On board the same aircraft are two other instruments, the cloud lidar system (CLS) and MODerate-resolution imaging spectrometer (MODIS) airborne simulator (MAS), which provide cloud cover information and independent measurements of W, respectively. The MIR-estimated W values are compared and found to be in very good agreement with those measured by rawinsondes at near concurrence. A close correlation is found between the MIR-estimated W and that estimated from the MAS near-IR reflectance ratios. Water surface emissivities at several MIR frequencies are obtained in the process of the W retrieval from several flights over the mid-west lakes. These estimated emissivities compared favorably with values calculated for a calm water surface, which are based on a recent dielectric permittivity model and MAS-measured surface temperatures. The results from all comparisons strongly demonstrate the soundness of the technique for estimating W.**

***Index Terms*—Millimeter-wave radiometry, remote sensing, water vapor.**

I. INTRODUCTION

MILLIMETER-WAVE radiometry with the strong absorption line of 183 GHz is normally used for profiling of water vapor, as both theoretical and experimental studies have demonstrated during the past two decades [1]–[5]. Additionally, some studies have shown that measurements near this line can be used to estimate total amount of water vapor column W for relatively dry atmospheric conditions that frequently occur in high latitude regions [6] or following a cold air outbreak [7]. Over Antarctica or the arctic region, dry-air conditions are prevalent from late fall to early spring so radiometry near 183 GHz provides an excellent resource for W estimation. Monitoring the state of atmospheric water vapor and its transport into and out of these regions is important toward our understanding the state of balance of ice sheets and its effect on global sea level [8]. Both Moore [9] and Miao [10] have selected Antarctica as their study area for estimation of W from measurements of the 183 GHz channels of the special sensor microwave/temperature-2 (SSM/T-2); however, the techniques employed by these authors are different. Moore [9] used measurements from the 183.3 $\pm$ 3 and 183.3 $\pm$ 7 GHz channels of the SSM/T-2, as well as the surface temperature derived from the European Center for Medium-range Weather Forecast (ECMWF) data source to simultaneously retrieve both W and surface reflectivity, R, using an iterative technique. Miao [10], on the other hand, used a regression approach with the SSM/T-2 measurements at 150, 183.3 $\pm$ 3, and 183.3 $\pm$ 7 GHz as inputs. R is assumed constant over the frequency range of 150–183 GHz in the latter approach.

Wang *et al.* [11] attempted to apply these techniques of Moore [9] and Miao [10] for estimation of W while using airborne MIR (Millimeter-wave Imaging Radiometer) measurements over Alaska and Arctic region on May 20, 1998 instead of the SSM/T-2 data. The flight is one of many conducted during the FIRE-ACE (First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment—Arctic Cloud Experiment) field campaign that occurred from May 18–June 6, 1998. However, the thermal IR channels of the MODIS (MODerate-resolution imaging spectrometer) airborne simulator (MAS) on board the same NASA ER-2 aircraft were not functioning properly during that clear day of flight and, thus, the analysis was limited to the technique of Miao [10]. In addition to the data from the frequency group of 150, 183.3 $\pm$ 3, and 183.3 $\pm$ 7 GHz that is needed for estimation of W, MIR also provided measurements at 220 GHz; therefore, W can be estimated independently using data from the frequency group of 220, 183.3 $\pm$ 3, and 183.3 $\pm$ 7 GHz. The results from both frequency groups can then be compared. Wang *et al.* [11] analyzed the MIR data from both frequency groups and found discrepancies of various amounts in the estimated W values. They attributed these discrepancies to the unsubstantiated assumption that R (or emissivity e) is constant across the frequency ranges of 150–183 GHz and 183–220 GHz. They modified the technique by allowing a linear dependence of e on frequency over the entire frequency range of 150–220 GHz; by varying the slope of this linear dependence, estimated Ws were forced to converge to a common value. The results obtained from this modified version of the technique appeared reasonable. The estimated W values were compared with the available rawinsonde data at two locations and the differences between the estimated and measured W values were within the accuracy of the radiometric measurements. A more extensive comparison with rawinsonde data was not possible, because all other flights from that mission were made when atmospheric conditions were too moist for the retrieval technique to be applicable.

In the following we extend the previous work of Wang *et al.* [11] to the MIR data obtained from the flights over the Midwest region of the continental U.S. during the WINter cloud experiment (WINCE) [12] of January/February 1997. The techniques of both Moore [9] and Miao [10] and its modified version are described and analyzed with simulated brightness temperatures from a vast number of rawinsonde data from the Alaskan, Arctic, and Midwest regions. The technique of Moore [9] is proven inadequate for application to the MIR data. The modified version of Miao's technique [11] is used exclusively to estimate W from the MIR measurements. The estimated W values from both FIRE-ACE and WINCE are compared with those derived from rawinsonde observations. Additionally, a comparison is made between these MIR-estimated Ws and those expected from the reflectance ratios in the near IR channels of the MAS. Finally, surface emissivities at several frequencies are estimated from a few observations over the lakes in the Midwest and compared with the calculated results, which substantiate the robustness of the retrieval technique.

V. Conclusions

Two different techniques [9], [10] developed recently for the estimation of integrated water vapor $W < 0.8$ g/cm^2 have been examined in this paper. The technique by Moore [9] utilizes the 183.3 $\pm$ 3 and 183.3 $\pm$ 7 GHz channels of the SSM/T-2 and ECMWF-derived surface temperature to estimate W and surface reflectivity R iteratively. Additionally, this approach requires as input an *a priori* optical-depth weighted effective atmospheric temperature in the equations for estimation of W and R. This latter requirement is found impractical for the data sets we obtained from the aircraft flights and therefore the technique is not explored further in the paper. The technique of Miao [10] is regression-based and uses the 150, 183.3 $\pm$ 3, and 183$\pm$ 7 GHz channels of the SSM/T-2 to estimate W over Antarctica. Equivalent surface emissivity values in the frequency range of 150–183 GHz are assumed in this approach, which, if not correct, could result in a significant error in the estimation of W [11]. MIR has an additional channel at 220 GHz that is absent from the SSM/T-2 and thus is capable of providing estimation of W with a simple linear dependence of e on frequency in the range of 150–220 GHz. Wang *et al.* [11] provided a demonstration of this modified version of Miao's technique using data from a clear-sky MIR flight over the Alaska-Arctic region on May 20, 1998. The present analysis extends that work to cover additional measurements over several different areas. Furthermore, the estimated W values are compared with those derived from the near IR channels of the MAS, as well as from a number of rawinsonde data. Additionally, as a by-product of the retrieval process, the surface emissivities at 89, 150, and 220 GHz for several lakes in the mid-west region of the continental U.S. are estimated and compared with results of calculations based on a recent dielectric permittivity model for fresh water [16].

The estimated W values are found to compare very well with those measured from the rawinsonde data for about the same time and location. On average the estimated W is about 0.02 g/cm^2 higher than the measured ground truth, which falls within the accuracy of the radiometric measurements. An increase of about 2 K in the measured brightness temperature at 150 GHz would offset this small bias [11]. The comparison between the MIR and MAS estimated W values is not exact because the estimation algorithm based on the reflectance ratios from the available near IR channels of the MAS is optimized for $W > 1$ g/cm^2 [15]. Interestingly, the variation in the scatter plot between the MIR estimated W and the MAS near IR reflectance ratios definitely show a significant correlation.

The estimated and calculated emissivities for fresh water are compared at three frequencies and over four different measurements. Except for a single case at 220 GHz, the estimated and calculated values agree very well. The small differences in the comparison can be accounted for either by considering measurement errors or inadequacy of extrapolation of the dielectric permittivity model to high frequencies. Together, the comparisons with rawinsonde data, MAS reflectance ratios, and emissivity calculations substantiate the soundness of the present regression approach for W estimation from the four-channel MIR measurements.

The technique presented here is useful for areas with relatively dry atmosphere conditions such as the Arctic region and Antarctica. However, it cannot be applied to the currently available satellite data, which are limited to three channels at 150, 183.3 $\pm$ 3, and 183.3 $\pm$ 7 GHz. Using data from these three channels alone requires an assumption of the same emissivity across the frequency range of 150–183 GHz [10], which could result in a significant error in W estimation [11]. Perhaps an improved method to better characterize surface type and, therefore, approximate frequency dependence of surface emissivity can be devised to resolve this problem. This is a nontrivial problem that remains to be pursued in future studies.

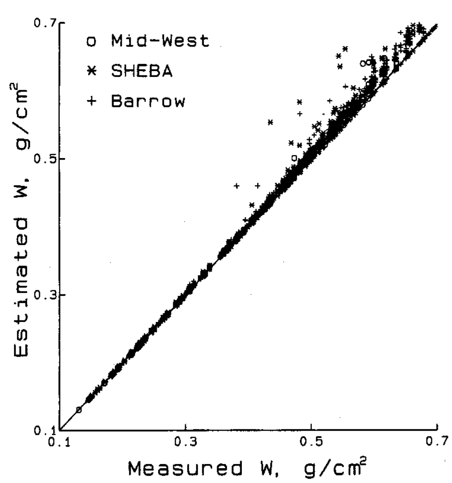

Fig. 1. Scatter plot of W values estimated from the simulated T_b(183.3 $\pm$ 3) and T_b(183.3 $\pm$ 7) and derived from the corresponding rawinsonde from Barrow, Alaska, SHEBA ship, and Mid-West. The surface emissivity is varied between 0.50–0.95 in 0.05 increments in the $T_b(\nu)$ calculations.